

Extreme hydrodynamic atmospheric loss near the critical thermal escape regime

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ABSTRACT

By considering martian-like planetary embryos inside the habitable zone of solar-like stars we study the behavior of the hydrodynamic atmospheric escape of hydrogen for small values of the Jeans escape parameter $\beta < 3$, near the base of the thermosphere, that is defined as a ratio of the gravitational and thermal energy. Our study is based on a 1-D hydrodynamic upper atmosphere model that calculates the volume heating rate in a hydrogen dominated thermosphere due to the absorption of the stellar soft X-ray and extreme ultraviolet (XUV) flux. We find that when the β value near the mesopause/homopause level exceeds a critical value of ~ 2.5 , there exists a steady hydrodynamic solution with a smooth transition from subsonic to supersonic flow. For a fixed XUV flux, the escape rate of the upper atmosphere is an increasing function of the temperature at the lower boundary. Our model results indicate a crucial enhancement of the atmospheric escape rate, when the Jeans escape parameter β decreases to this critical value. When β becomes ≤ 2.5 , there is no stationary hydrodynamic transition from subsonic to supersonic flow. This is the case of a fast non-stationary atmospheric expansion that results in extreme thermal atmospheric escape rates.

Key words: planets and satellites: atmospheres – planets and satellites: physical evolution – ultraviolet: planetary systems – stars: ultraviolet – hydrodynamics

1 INTRODUCTION

Studies related to hydrodynamic escape and evolution of planetary atmospheres (e.g., Sekiya et al. 1980a, 1980b, 1981; Watson et al. 1981; Kasting & Pollack 1983; Yelle 2004; Tian et al. 2005a, 2005b; Murry-Clay et al. 2009; Koskinen et al. 2013; Erkaev et al. 2013, 2014; Lammer et al. 2013a, 2014) indicate that the heating of the upper atmosphere caused by high XUV radiation and the related hydrodynamic expansion of the bulk atmosphere is important for the escape of light gases such as hydrogen from early planetary atmospheres. The hydrodynamic outflow of the atmospheric particles is somewhat similar to that of the solar wind described by the well known isothermic model of Parker (1964a, 1964b). For escape, the atmospheric gas requires a heating source to overcome the gravitational potential of the planetary body. The main heating source in planetary atmospheres is provided by the host star in the form of XUV radiation and its absorption in the upper atmosphere.

In their pioneering study Watson et al. (1981) proposed an analytical hydrodynamic escape model, where the XUV

heating was assumed to be deposited within a thin layer near the planetary surface. In reality the XUV flux is absorbed over a wider altitude range (e.g., Tian et al. 2005a; Murry-Clay et al. 2009). For instance, Murray-Clay et al. (2009) applied a more realistic upper atmosphere heating model where the XUV volume heating rate Q_{XUV} can be written as

$$Q_{\text{XUV}} = \eta I_{\text{XUV}0} \exp(-\tau) \sigma n, \quad (1)$$

with a heating efficiency η that corresponds to the fraction of the absorbed XUV radiation that is transformed into thermal energy (Shematovich et al. 2014), the XUV absorption cross section σ_{XUV} which is $\sim 5 \times 10^{-18} \text{ cm}^2$ for a hydrogen dominated atmosphere (Beyont & Cairns 1965), the neutral atmosphere density n , and optical depth τ

$$\tau = \sigma \int_r^\infty n dr. \quad (2)$$

This XUV heating model was further extended by Erkaev et al. (2013) by taking into account the angular dependence of the heating rate. Generally, the main necessary condition for hydrodynamic escape modeling is that the sonic point

should be within the collision dominated atmosphere where the Knudsen number Kn is sufficiently small. Volkov et al. (2011) suggested a criterion where hydrodynamic models should be valid without problems as long as the $Kn \leq 0.1$.

In our present study we investigate the escape criteria and efficiency of atomic hydrogen from a Mars-like planetary embryo at 1 AU that experiences XUV flux values between 45–100 times higher than that of today's solar value. A relatively low gravity and temperatures at the base of the thermosphere that are ≥ 250 K provide low values of the Jeans escape parameter β

$$\beta = \frac{GM_{\text{pl}}m}{kTR}, \quad (3)$$

which can cause a crucial enhancement of the hydrodynamic atmospheric escape rates. With G Newton's gravitational constant, M_{pl} the mass of a planet, m the mass of the atmospheric main species, Boltzmann constant k , atmospheric temperature T and planetocentric distance R . For large gas giants such as Jupiter the β value at the base of the thermosphere is ~ 474 and for hot Jupiter's such as HD209458b the thermosphere base β value is ~ 313 , while at a distance of $\sim 3R_{\text{pl}}$ β decreased to ~ 5.6 . For low mass planetary bodies such as the building blocks of terrestrial planets like martian size planetary embryos that outgassed volatiles which produced steam atmospheres during the solidification of magma oceans (Elkins-Tanton 2012), or nebula captured hydrogen gas (Lammer et al. 2014), that are exposed by the high XUV flux of young host stars inside the habitable zone β near the base of the thermosphere can reach values that are < 3 .

With this in mind, the main aim of our study is to investigate the behavior of the hydrodynamic atmospheric expansion of a hydrogen dominated upper atmosphere for low β values. In Sect. 2 we describe the model approach, in Sect. 3 we present and discuss our analytical and numerical results and their relevance for the evolution of initial water inventories of terrestrial planets.

2 MODEL EQUATIONS

2.1 Hydrodynamic upper atmosphere model

To study the XUV-heated upper atmosphere structure and thermal escape rates of exposed hydrogen atoms, we apply a 1-D hydrodynamic upper atmosphere model with an energy absorption model, that is described in detail in Erkaev et al. (2013, 2014) and Lammer et al. (2013a, 2014). The model solves the system of the hydrodynamic equations for mass,

$$\frac{\partial \rho R^2}{\partial t} + \frac{\partial \rho v R^2}{\partial R} = 0, \quad (4)$$

momentum,

$$\frac{\partial \rho v R^2}{\partial t} + \frac{\partial [R^2(\rho v^2 + P)]}{\partial R} = \rho g R^2 + 2PR, \quad (5)$$

and energy conservation,

$$\frac{\partial R^2 \left[\frac{\rho v^2}{2} + \frac{P}{(\gamma-1)} \right]}{\partial t} + \frac{\partial v R^2 \left[\frac{\rho v^2}{2} + \frac{\gamma P}{(\gamma-1)} \right]}{\partial R} = \rho v R^2 g + Q_{\text{XUV}} R^2. \quad (6)$$

The distance R corresponds to the radial distance from the centre of the planet, ρ, P, T, v are the mass density, pressure,

temperature and velocity of the XUV exposed and heated non-hydrostatic outward flowing bulk atmosphere. γ is the polytropic index, g the gravitational acceleration and Q_{XUV} is the XUV volume heating rate (Erkaev et al. 2013, 2014)

$$Q_{\text{XUV}} = \eta \sigma_{\text{XUV}} n I_{\text{XUV}}^* \frac{1}{2} \int_0^{\pi/2 + \arccos(1/r)} J(r, \theta)_{\text{XUV}} \sin(\theta) d\theta, \quad (7)$$

where r is the normalized radial distance $r = R/R_0$, R_0 is the lower boundary radius at the base of the thermosphere near the mesopause/homopause level, η is the heating efficiency which is typically 15% (Shematovich et al. 2014), I_{XUV}^* is the XUV flux at the upper boundary, σ_{XUV} is the XUV absorption cross section in a hydrogen atmosphere (Chassefière 1996; Erkaev et al. 2013; Lammer et al. 2014), and $J(r, \theta)_{\text{XUV}}$ is a dimensionless function describing the variation the XUV flux with respect to the radial distance due to the atmospheric absorption,

$$J(r, \theta)_{\text{XUV}} = \exp \left[- \int_r^{R^*} a \tilde{n}(\xi) (\xi^2 - r^2 \sin(\theta))^{-1/2} \xi d\xi \right]. \quad (8)$$

Here R^* is the upper boundary radius, $\tilde{n} = n/n_0$, where n_0 is the normalized density at the lower boundary, and $a = \sigma_{\text{XUV}} n_0 R_0$ is a dimensionless constant parameter. Formula (8) describes the XUV flux intensity as a function of spherical coordinates r and θ . In the particular case when $\theta=0$, this formula can be simplified to the expression

$$J(r, \theta)_{\text{XUV}} = \exp(-\tau), \quad (9)$$

where τ is given by equation (2). Therefore, our heating model is quite similar to that of Murray-Clay et al. (2009) for the central radial direction with zero spherical angle.

In case of a stationary outflow regime, we can neglect the time derivatives and obtain the ordinary system of equations as follows

$$\rho v R^2 = \Psi, \quad (10)$$

$$\rho v \frac{\partial v}{\partial R} + \frac{\partial P}{\partial R} = -\rho \frac{\partial \Phi}{\partial R}, \quad (11)$$

$$\frac{\partial \Psi \left[\frac{v^2}{2} + \frac{\gamma P}{(\gamma-1)\rho} + \Phi \right]}{\partial R} = Q_{\text{XUV}} R^2, \quad (12)$$

where Φ is the gravitational potential, and Ψ is the escaping mass flux per unit steradian.

Integrating equation (12) we get a relationship between the escape rate and the total absorbed energy.

$$\Psi = \frac{\int_1^{R^*} Q_{\text{XUV}} R^2 dR}{[v^{*2}/2 + \Delta\Phi - v_0^2/2 - \gamma/(\gamma-1)(kT_0/m)]}. \quad (13)$$

Here v_0 and v^* are the flow velocities at the lower and upper boundaries. The total absorbed energy (energy deposition) is related to the incoming XUV flux

$$4\pi \int_1^{R^*} Q_{\text{XUV}} R^2 dR = \eta I_{\text{XUV}}^* \pi R_{\text{eff}}^2, \quad (14)$$

where R_{eff} is the effective XUV absorption radius

$$R_{\text{eff}} = R_0 \left[1 + \int_1^{\tilde{R}^*} (1 - \tilde{J}(s, 0)) 2s ds \right]^{1/2}, \quad (15)$$

Introducing definition $\beta = m\Delta\Phi/(kT_0)$, and using (14) we rewrite equation (13)

$$4\pi\Psi = \frac{\eta I_{\text{XUV}}^* \pi R_{\text{eff}}^2}{\Delta\Phi} A, \quad (16)$$

$$A = \frac{1}{[1 + (v^{*2} - v_0^2)/(2\Delta\Phi) - \gamma/[(\gamma - 1)\beta]]}. \quad (17)$$

For large values of the Jeans escape parameter β , the effective radius R_{eff} is close to the base of the thermosphere R_0 , the ratio $v^{*2}/\Delta\Phi$ can then be neglected and the coefficient $A \approx 1$. In such a case equation (16) yields the well known energy limited escape formula

$$4\pi\Psi = \frac{\eta I_{\text{XUV}}^* \pi R_{\text{eff}}^2}{\Delta\Phi}. \quad (18)$$

In cases of a small β value near R_0 , the escape rate becomes much larger than that predicted by the energy limited escape formula (13) because the effective radius (R_{eff}) increases substantially, and in equation (13) the terms kT/m and $\Delta\Phi$ become comparable to each other. These terms become equal to each for a critical value of β

$$m\Delta\Phi/(kT_0) = \beta_c = \frac{\gamma}{\gamma - 1}. \quad (19)$$

In such a case the enthalpy of the lower atmospheric gas is large enough to provide expansion of the atmosphere against gravity, and an additional heating is not needed for that. The escape rate is expected to have a pile-up when the Jeans escape parameter β approaches to β_c .

3 ANALYTICAL AND NUMERICAL RESULTS

The system of equations (10, 11, 12) can be transformed to a pair ordinary differential equations with respect to the normalized entropy and velocity

$$\frac{dS}{dr} = \frac{(\gamma - 1)\tilde{q}r^{2(\gamma-1)}}{\tilde{V}^{(2-\gamma)\Gamma(\gamma-1)}}, \quad (20)$$

$$\frac{d\tilde{V}}{dr} = \frac{\tilde{V}}{r} \frac{\left[\beta/r - 2\gamma S \left(\frac{\Gamma}{\tilde{V}r^2} \right)^{\gamma-1} + (\gamma - 1) \frac{r\tilde{q}}{\tilde{V}} \right]}{\left[\gamma S \left(\frac{\Gamma}{\tilde{V}r^2} \right)^{\gamma-1} - \tilde{V}^2 \right]}. \quad (21)$$

Here Γ is the normalized escape rate

$$\Gamma = \frac{\Psi}{(n_0 \sqrt{kT_0/m} R_0^2)}, \quad (22)$$

S is the entropy-like function, $S = \tilde{P}/\tilde{n}^{\gamma-1}$, \tilde{P} is the normalized pressure, $\tilde{P} = P/(n_0 kT_0)$, \tilde{V} is the normalized velocity $\tilde{V} = V/\sqrt{kT_0/m}$, r is the normalized distance, $r = R/R_0$, and \tilde{q} is the normalized heating rate per one particle

$$\tilde{q} = \frac{Q_{\text{XUV}} \sqrt{m} R_0}{n(kT_0)^{3/2}}. \quad (23)$$

The denominator of equation (21) means a difference between the sonic speed squared and the bulk velocity squared. At the sonic point, where the denominator vanishes, the numerator must vanish as well. In the subsonic region the denominator becomes positive, and thus the numerator should be also positive in the most part of the region below the sonic point in order to provide an acceleration of the flow. However, near the lower boundary the numerator can be

negative in case of a low β . Therefore, for a low β the numerator has to change its sign in the subsonic region and at the sonic point. In such a case, the velocity behavior is not monotonic. First it decreases near the lower boundary, and then it starts to increase until the sonic point. There are two ways for finding the escape rate and radial profiles of the velocity, density and temperature.

The first way is to apply the so-called shooting method for solving the ordinary differential equations with the boundary condition at the sonic point. This method will allow us to determine the unknown escape rate Γ . For the particular unique value of the escape rate it is possible to pass by the sonic point from the subsonic lower boundary to the supersonic upper boundary.

The second way is to use the time relaxation method by solving the non-steady system of the hydrodynamic equations. We find the numerical solution by a finite difference numerical scheme described in the previous publications of Erkaev et al. (2013). Steady-state profiles are obtained by time relaxation of the numerical solution. We used both methods mentioned above and obtained similar results. In particular we investigate the behavior of the solution when the escape parameter β becomes close to the critical value $\gamma/(\gamma - 1)$.

The results shown in Figs. 1–3 and Table 1 are based on an assumed hydrogen dominated upper atmosphere that originated either from a hot steam atmosphere or nebula captured hydrogen gas above a planetary body with the size and mass of Mars in an orbit inside the habitable zone of a Sun-like star. The high XUV fluxes of young solar-like stars will most likely dissociate hydrogen bearing molecules such as H_2O or H_2 and in the upper atmosphere so that it should be mainly dominated by atomic hydrogen (Kasting & Pollack 1983; Chassefière 1996; Yelle 2004; Lammer 2013). During such protoatmosphere conditions one can expect that the surface is much hotter (i.e. solidified magma ocean, magma ocean in mush stage, surface bombarded frequently by planetesimals) compared to that of present Mars in the Solar System (e.g., Marcq 2013; Lebrun et al. 2013; Erkaev et al. 2014; Lammer et al. 2014). Because of this, the results of 1-D radiativeconvective atmospheric models that studied the coupling between hot planetary surfaces and surrounding steam atmospheres (Marcq 2012) indicate that the mesopause/homopause level z_0 of low mass bodies such as Mars may extend from ~ 100 km as on present day Mars up to distances that can be located a few 100 Kilometer higher. For this reason we assume our lower boundary conditions at a distance $R_0 = R_{\text{pl}} + z_0$ with $z_0 = 433$ km, with a mesopause/homopause temperature that correspond to the equilibrium or skin temperature at 1 AU, assumed to be $T_0 = 247$ K ($\beta = 2.9$), 256 K ($\beta = 2.8$), and 266 K ($\beta = 2.7$). For the number density at that level we assume a similar value $n_0 = 5 \times 10^{12} \text{ cm}^{-3}$ (e.g., Tian et al. 2005b; Erkaev et al. 2013, 2014; Lammer et al. 2013, 2014).

On the left hand side, Fig. 1 shows the analytical Mach number profiles corresponding to three different values of velocity at the lower boundary and a Jeans escape parameter β of 2.7. On the right hand side, this figure shows the analytical velocity profiles, and also the numerical profile for $\beta = 2.7$. The numerical one is obtained by time relaxation method based on the finite difference numerical scheme described in Erkaev et al. (2013). The analytical curves are

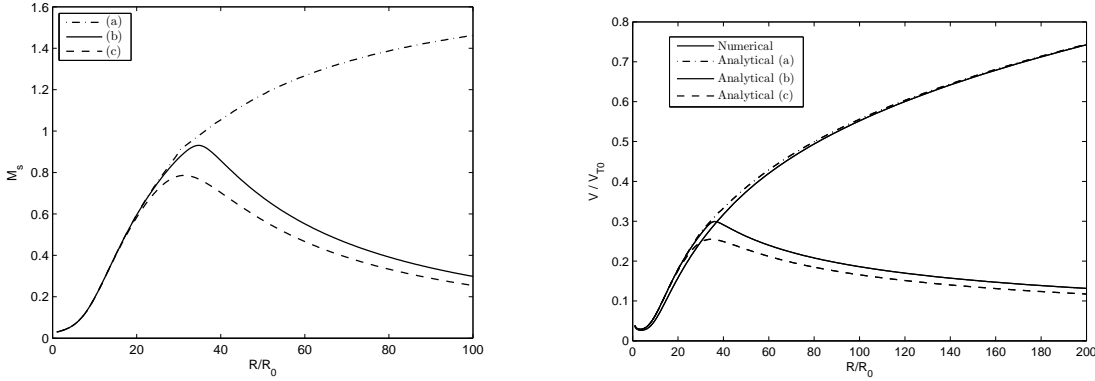


Figure 1. Left hand side: Analytical sonic Mach number profiles for $\beta = 2.7$. Right hand side: Analytical and numerical velocity profiles for $\beta = 2.7$; here curves (a), (b), and (c) correspond to different initial velocity values: 0.03843, 0.03841 and 0.0383, respectively.

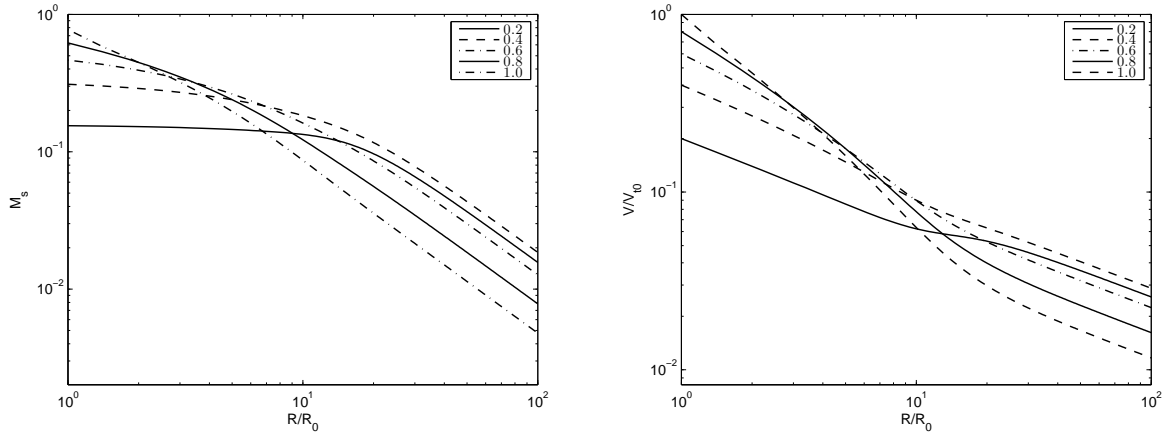


Figure 2. Analytical Mach number profiles (left) and velocity profiles (right) corresponding to different initial velocities for $\beta = 2.5$

obtained by the integration of equations (21, 21) for three different initial velocity conditions: $V_0 = 0.03843$, 0.03841 and 0.0383. The true initial value $V_0 = 0.03843$ corresponds to a separatrix, which provides acceleration of particles from subsonic to supersonic values. This separatrix is rather close to the profile obtained by the numerical relaxation method.

Fig. 2 shows the analytical sonic Mach number and velocity profiles corresponding to a lower β parameter value of 2.5. In this case ($\beta = 2.5$), there is no acceleration at all, when the lower boundary velocity is subsonic. By considering different subsonic velocity conditions, we obtain only decreasing velocity functions. For any subsonic velocity conditions at the lower boundary, the velocity does not have monotonic increase until supersonic values. Our results show that the escape rate increases enormously, when the escape parameter β approaches its critical value.

Fig. 3 shows the normalized escape rate (per sterad.) and the total escape rate (per sec.) as functions of the Jeans escape parameter β for XUV flux values that are 45 and 100 times higher compared to that of today's Sun. For a quite small decrease of the β parameter, the escape rate increases by a factor of 10. However, the sonic point position, and the corresponding velocity and temperature have a minor change when the escape rate is approaching the critical

value. An exception is the density at the sonic point, which has a substantial increase proportionally to the escape rate.

Table 1 presents the total escape rate, effective radius, and also hydrodynamic parameters such as the flow velocity, density and temperature corresponding to two particular points. The first one (R_s) is the sonic point where the sonic Mach number is ~ 1 . The second one (R^*) is the point where the Knudsen number is ~ 0.1 . The model results are based on the Jeans escape parameter β near the mesopause/homopause level for three values near the critical one, namely 2.7, 2.8, and 2.9 and two XUV flux intensities that are 45 and 100 times higher than that of today's solar value.

One can see that with our assumed input parameters, hydrodynamic conditions are valid far beyond R_s is reached. The escape rate rises up to ~ 3 times if the β value near the critical one, changes only slightly from 2.9 to 2.7. Thus, extreme uncontrolled blow-off will occur for smaller values.

Chamberlain (1963) and Watson et al. (1981) described $\beta = 1.5$ as a critical value for atmospheric “blow-off” corresponding to the case when the thermal energy is equal to the gravitational energy. In the model of Parker (1964a, 1964b), the critical β value is equal to 2. For lower values of β , a hydrodynamic flow cannot have transition from subsonic to a

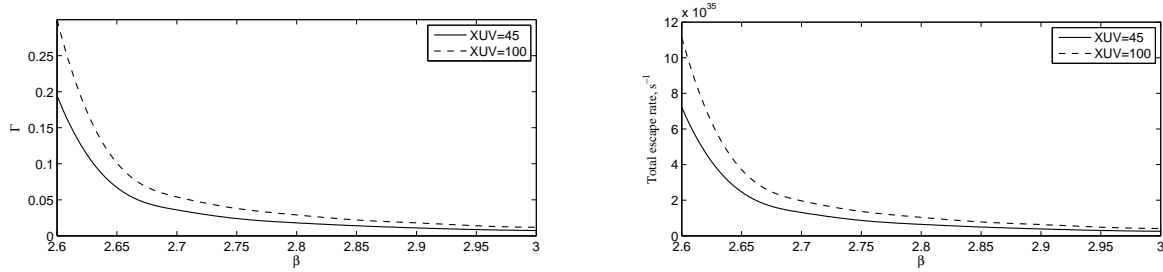


Figure 3. Normalized escape rate (per sterad.) and the total escape rate (per sec.) as functions of the Jeans escape parameter β for XUV flux values that are 45 and 100 times higher compared to that of today's Sun.

Table 1. Main parameters characterizing the hydrodynamic escape flow from a martian-like body at 1 AU, surrounded by a hydrogen envelope (i.e., dissociated H_2O molecules, captured hydrogen from a planetary nebula: R_s is the sonic point distance, and R^* is the distance where the Knudsen number is ~ 0.1). The β values of 2.9, 2.8 and 2.7 correspond to T_0 values neat the mesopause/homopause level of 247 K, 256 K, and 266 K, respectively.

XUV	Escape rate, 10^{33} s^{-1}	R_{eff}/R_0	R_s/R_0	V_0/V_{T_0}	N_s/N_0	T_s/T_0	R^*/R_0	V^*/V_{T_0}	$N^*/N_0, 10^{-9}$	T^*/T_0	β
45	128	13	40	0,31	70	0,06	8000	2,6	0,29	1,4	2,7
45	64	10	40	0,31	35	0,06	4500	2,1	0,48	0,9	2,8
45	40	9	39	0,32	34	0,06	3000	1,9	0,66	0,7	2,9
100	199	13	31	0,37	143	0,08	8000	3,5	0,25	2,3	2,7
100	105	10	31	0,37	81	0,08	5000	2,9	0,46	1,7	2,8
100	63	9	30	0,38	54	0,08	3300	2,5	0,66	1,3	2,9

supersonic regime. A continuous acceleration is possible only in the supersonic regime. This means that the flow velocity should be supersonic already at the lower boundary.

From our hydrodynamic model we find the critical β parameter is ~ 2.5 , which corresponds to a condition that the enthalpy is equal to the gravitational energy. It is also worth to mention that our results agree with the kinetic simulations of Volkov et al. (2011) whose simulations yield a very sharp growth of the escape rate, when the β parameter decreases from 2.7 to 2. For β values ≤ 2 this kinetic simulations predict only supersonic flow. For larger β values the kinetic model of Volkov et al. (2011) predicts only subsonic flow because it does not have heating above R_0 because the incoming XUV radiation was assumed to be absorbed around R_0 . Our model includes a strong XUV heating above R_0 , and therefore we have acceleration from a subsonic to a supersonic regime for $\beta > 2.5$.

Small β values can be reached on smaller planetary bodies such as planetary embryos after magma oceans solidified (e.g., Lammer et al. 2013b; Lebrun et al. 2013), or lower mass hydrogen-dominated exoplanets in close orbital distances. One can see from Table 1, Mars-type bodies with hydrogen dominated upper atmospheres will reach this critical conditions quite easy. Smaller bodies will reach the critical hydrodynamic escape regime even easier. Under extreme conditions the atmosphere at the base of the thermosphere may be hot so that a supersonic flow can occur around the mesopause/homopause level. Such a very fast non-steady expansion of an atmosphere may act like an explosion that enhances the loss of water from the building blocks of the terrestrial planets, that may finally accrete drier as expected.

H_2O and other volatiles may be stepwise outgassed and potentially lost to a great extent, as illustrated in Fig. 10 in Lammer et al. (2013b), before accretion ends. If wet planetary embryos lose much of their initial H_2O by fast hydrodynamic escape during their growth to the final planetary body, the volatile content that is outgassed in the final stage would be lower than expected. Such a scenario would agree with the hypothesis of Albarède and Blichert-Toft (2007), which is that the terrestrial planets in the Solar System accreted dry and obtained most of their water during the late veneer via impacts.

However, the fast expansion will be connected by strong adiabatic cooling which has a feedback on the β parameter, that will grow above the critical value where a stationary hydrodynamic escape regime will most likely be established.

4 CONCLUSION

Analyzing the hydrodynamic atmospheric escape solutions for a hot martian-type planetary body (i.e., large planetary embryos in an inner planetary system, etc.), we found a critical value for the Jeans escape parameter $\beta_c \sim 2.5$ corresponding to a bifurcation of the atmospheric expansion regime. A hydrodynamic flow acceleration from subsonic to supersonic velocities is possible for β values that exceed this critical value. The true value of the escape rate corresponds to the separatrix velocity profile, which goes from the lower boundary through the sonic point towards infinity. The escape rate is found to increase crucially, when β approaches the critical value. When β is below the critical value, the velocity becomes supersonic even at the lower boundary.

Regarding this, the following scenario is expected. A supersonic flow at the lower thermosphere means a very fast non-steady expansion of the atmosphere like an explosion. This expansion might cause a strong adiabatic cooling of the atmosphere. Such process might result in a decrease of the temperature, and consequently an increase of the β parameter. Finally the β parameter will grow above the critical value, and thus a stationary hydrodynamic escape can be established.

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